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Design and Performance of Single-Well Tracer Tests at the Mobile Site

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16. ABSTRACT

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Design and Performance of Single-Well Tracer Tests at the Mobile Site

FRED J. MOLZ, JOEL G. MELVILLE, OKTAY GÜVEN
RONALD D. CROCKER, AND KEITH T. MATTESON

Department of Civil Engineering, Auburn University, Alabama

Tracer tests are the most reliable field methods for obtaining information describing advection and dispersion in aquifers. This paper describes the design and performance of single-well tracer tests utilizing multilevel observation wells at a field site near Mobile, Alabama. In a given observation well, a total of 7 sampling zones were isolated using inflatable packers and silicone rubber plugs. All instrumentation was contained within a removable insert that extended from the well bottom to the land surface. Each sampling zone contained an electrical conductivity probe and was connected to the surface with two lengths of vacuum tubing. When combined with peristaltic pumps, the tubing allowed mixing of the sampling zone contents as well as water sample collection. A total of 5 experiments were performed using bromide as a conservative tracer. Results showed that the sampling zones were well isolated and that sampling zone mixing was necessary to achieve results that were independent of probe placement within a given zone. Both electrical conductivity and bromide concentration breakthrough curves indicated the presence of a high horizontal permeability zone in the bottom third of the aquifer, although the concentration data were considered the more accurate and reliable. Permeability values based on tracer travel times from the injection-recovery well to the multilevel observation well varied by a factor of 4 over the aquifer thickness. Such results are reasonably consistent with permeability trends inferred during thermal energy storage experiments performed previously at the same site.

1. INTRODUCTION

Several recent studies of dispersion in saturated porous media have reemphasized the importance of nonuniform but nonrandom advection patterns in the dispersion process [*Pickens and Grisak*, 1981; *Molz et al.*, 1983*b*; *Gillham et al.*, 1984; *Güven et al.*, 1984; *Osiensky et al.*, 1984; *Güven et al.*, 1985; O. Güven et al., unpublished manuscript, 1985]. An important aquifer property which arose from such studies was the variation of horizontal hydraulic conductivity in the vertical direction, which we will refer to as $K(z)$. For the case of horizontal flow in a perfectly stratified aquifer, $K(z)$ completely describes the nonhomogeneity. Obviously, in natural aquifers there is also variation of K in the lateral directions. Even with lateral variability, however, natural aquifer flows can be predominantly horizontal. Small values of vertical hydraulic conductivity, small vertical head gradients, or gradually changing geometry of lens-shaped nonhomogeneities all contribute to nearly horizontal flow over significant distances. Proper interpretation of field data or predictive modeling for nearly horizontal flow is strongly dependent on the $K(z)$ function.

It is generally agreed that tracer tests are currently the most reliable field methods for obtaining data to describe advection and dispersion in an aquifer. There are three main classes of tests: (1) single-well tests, (2) natural gradient tests, and (3) double-well tests. We are concerned here with single-well tracer tests which may involve continuous tracer injection or injection of tracer pulses. In a single-well test a conservative tracer solution is simply pumped into the formation for a period of time and then recovered. The concentration of tracer in the withdrawn water is measured and recorded as a function of time. In addition, one or more nearby multilevel observation wells may be used to obtain concentration data from discrete locations at different depths in the formation during the injection and withdrawal pumping.

Pickens and Grisak [1981] performed detailed single-well and two-well tracer tests in a shallow, unconfined, granular aquifer that was fairly well stratified, at least in the vicinity of the tests. Their measured $K(z)$ distributions contained information adequate to perform quite accurate simulations of their experiments [*Molz et al.*, 1983*b*; *Güven et al.*, 1984; *Güven et al.*, 1985] using constant local hydrodynamic dispersivities of less than 1 cm.

The purpose of the present paper is to describe the design and performance of single-well tracer tests at a field site near Mobile, Alabama. The tests were similar in concept to those of *Pickens and Grisak* [1981] but were conducted in a deeper confined aquifer and on a larger scale. Multilevel observation wells were installed, but the well construction and sampling technique employed by Pickens and Grisak could not be utilized due to the depth and size of the experiment.

2. WELLFIELD DESIGN, CONSTRUCTION, AND TESTING

The project site is located in a soil borrow area at the Barry Steam Plant of the Alabama Power Company, about 32 km north of Mobile, Alabama. The surface zone is composed of a low-terrace deposit of Quaternary age consisting of interbedded sands and clays that have, in geologic time, been recently deposited along the western edge of the Mobile River. These sand and clay deposits extend to a depth of approximately 61 m where the contact between the Tertiary and Quaternary geologic eras is located. Below the contact, deposits of the Miocene series are found that consist of undifferentiated sands, silty clays, and thin-bedded limestones extending to an approximate depth of 305 m.

2.1. *Well Field Design*

The well field at the Mobile site was established over the past decade in the Quaternary deposits, and the portion constructed or utilized for the present experiments is shown to scale in Figure 1. The study aquifer is well confined above and below by clay-bearing strata that extend laterally for several thousand feet or more, and the natural piezometric surface of the confined aquifer at the test site is approximately at a depth of 2–3 m below the ground surface. In experiments performed to date, vertical hydraulic gradients within the aquifer have appeared negligible. A medium to fine sand containing ap-

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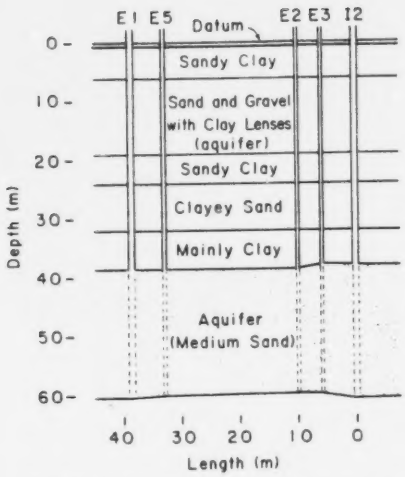

Fig. 1. Diagram of the subsurface hydrologic system along with various tracer injection and recovery and observation wells at the Mobile site.

proximately 3% silt and clay by weight composes the main aquifer matrix at well E3. (At other locations in the aquifer the fines varied from 1 to 15% by weight.) Details concerning aquifer-aquitard hydraulic and other physical properties may be found in the work by *Parr et al.* [1983]. Wells E1 and I2 are pumping wells that are used to inject and/or recover tracer solution, while E2, E3, and E5 are multilevel observation wells. In the experiments to be reported, only E3 and E5 were actually instrumented. When E3 was constructed, disturbed cores were obtained at seven locations throughout the depth of the study aquifer. The resulting particle size and distribution data are presented in Table 1.

The pumping wells are constructed of 20.3 cm (8 in) steel casings with 15.2 cm (6 in) stainless steel, wire wrapped screens, and the observation wells are constructed of 15.2 cm (6 in) polyvinyl chloride casings with 10.2 cm (4 in) partly slotted PVC screens. As is shown in Figure 2, the screened portion of the multilevel observation wells are not of a standard design. The screens themselves are composed of 21 cm (3 ft) slotted sections alternating with 213 cm (7 ft) solid sections. Although four slotted sections are shown in Figure 2 for purposes of illustration, the actual screens contained seven slotted sections.

As is also shown in Figure 2, a 5.1 cm (2 in) diameter PVC insert was constructed with slotted and solid portions that matched with those of the observation well screen. The insert

TABLE 1. Particle Size Distribution Data for the Seven Disturbed Cores Obtained During Construction of Well E3

Depth of Core, m	D_{60}, mm	D_{30}, mm	D_{10}, mm	Percent Passing No. 200 Sieve, %
40.2	0.46	0.35	0.21	1.8
43.3	0.36	0.26	0.13	1.4
46.6	0.58	0.45	0.21	3.0
49.7	0.46	0.27	0.12	5.6
52.7	0.49	0.28	0.15	3.5
56.1	0.59	0.44	0.26	1.2
59.1	0.94	0.56	0.19	3.8

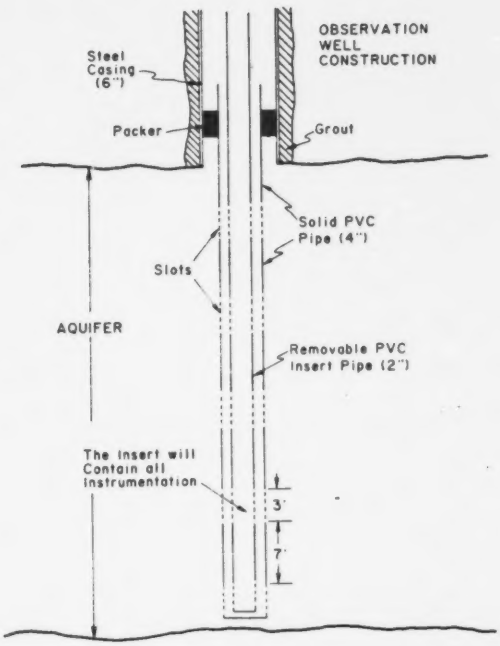

Fig. 2. Schematic diagram of the basic construction plan for a multilevel observation well with a removable insert.

was designed to hold any wires, tubing, or instrumentation that ultimately would be placed in an observation well. Composed of threaded 3.5 m (10 ft) sections, the inserts extended all the way to the land surface. In order to isolate the various sampling zones, they were fitted externally with cylindrical annular inflatable packers as illustrated in Figures 3 and 4.

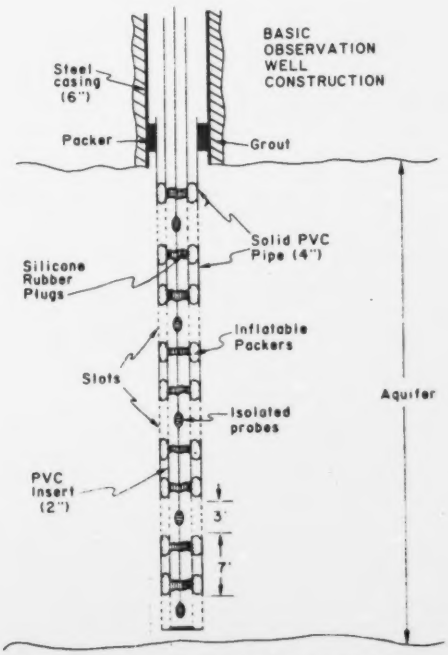

Fig. 3. Multilevel observation well with sampling zones that are isolated with inflatable packers and silicone rubber plugs.

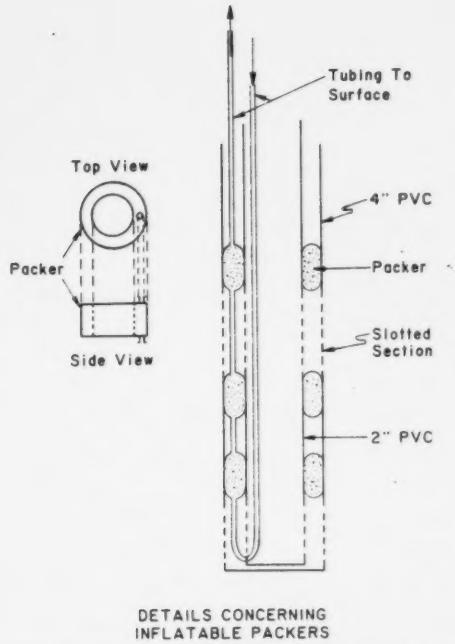

Fig. 4. Details concerning the geometry and installation of inflatable packers; packers were inflated with water.

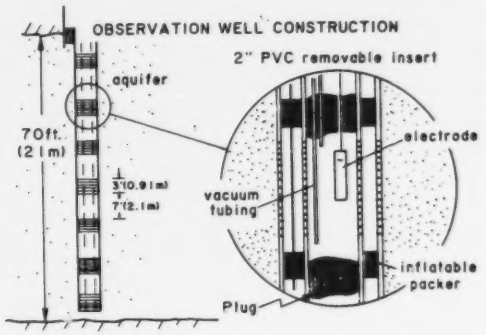

Fig. 5. Schematic diagram of a completed multilevel observation well.

After the required probes, tubing and wires were placed within the inserts, and the sampling sections were isolated internally with silicone rubber plugs. The complete insert was constructed on the surface, then placed in the well, positioned, and the packers inflated. Table 2 lists the sampling zone elevations. After installation, each isolated 91 cm (3 ft) sampling zone appeared as shown in Figure 5. A conductivity probe was placed near the zone center, and two lengths of vacuum tubing connected the sampling zone to the surface. This tubing could be used with peristaltic pumps to mix the contents of the sampling zone and also to obtain groundwater samples for analysis.

In the several experiments reported herein, tracer solution was injected through well I2. Supply water was obtained from a well (S2) screened in the study aquifer about 244 m east of I2. This separation was sufficiently large so that the hydraulic effects of S2 pumping did not affect the tracer experiments in the vicinity of I2. Concentrated tracer solution was mixed in a 4800 liter tank and added to the 10.2 cm pipeline connecting S2 and I2 using a metering pump. The pipeline travel distance from the metering pump to the study aquifer was at least 160 m, which was more than sufficient to insure complete mixing of the tracer. It was assumed that the piezometric head distribution in the injection well screen was uniform with depth, since the screen diameter was 15.24 cm, which resulted in a maximum average vertical fluid velocity in the screen of 0.84 m/s (during experiment 4). Thus the maximum velocity head was only 0.036 m and the head losses due to friction along the 21 m length of screen would be less than 0.10 m. These totals when compared to the total injection head of approximately 3 m are consistent with the assumption of constant head in the well screen interior.

2.2. *Observation Well Performance Test*

The major purpose of a multilevel observation well is to determine tracer travel times and breakthrough curves at distinct levels in an aquifer; to accomplish this the levels must be isolated. In order to develop some idea of the degree of isolation achieved with the present observation well construction scheme, two partially penetrating tracer injection tests with and without packers inflated were performed. The two wells used in the test were E3 and I2 (Figure 1), but with the lower 12 m of the I2 screen packed off. This was done so that definite vertical gradients would be established in the aquifer. In experiment 1 (conductivity probes hanging in the E3 screen, no packers or silicone rubber plugs) a sodium bromide tracer solution of about 300 mg/L was injected at an average rate of 0.605 m^3/min (133 gpm) for 17.5 hours. This was followed by an additional 27.9 hours of water injection (no tracer added) before injection was halted and the tracer recovered. In experiment 2 (packers inflated, silicone rubber plugs in place) a sodium bromide tracer solution of approximately 340 mg/L was injected at an average rate of 0.632 m^3/min (139 gpm) for 17.7 hours. Untraced water was injected for an additional 6.65

TABLE 2. Sampling Zone Elevations, Arrival Times for 50% Breakthrough, Apparent Dispersivity Values, and Inferred Relative Permeability Values for Experiment 4

Level No.	Midzone Elevation, m	$t_{0.5}$ From Data, h	Relative Permeability	Apparent Dispersivity, m	$t_{0.5}$ From Conductivity Data, h	Relative Permeability
1	−40.7	33.4?	0.24	0.07 ± 0.01	29.0	0.34
2	−43.8	24.3	0.33	0.18 ± 0.02	27.3	0.37
3	−46.8	20.5	0.39	0.17 ± 0.06	...	...
4	−49.9	14.0	0.57	0.12 ± 0.04	16.0	0.63
5	−52.9	19.0	0.44	0.32 ± 0.08	21.8	0.46
6	−56.0	8.0	1.00	0.50 ± 0.03	10.0	1.00
7	−59.0	32.4	0.25	0.04 ± 0.01	33.2	0.30

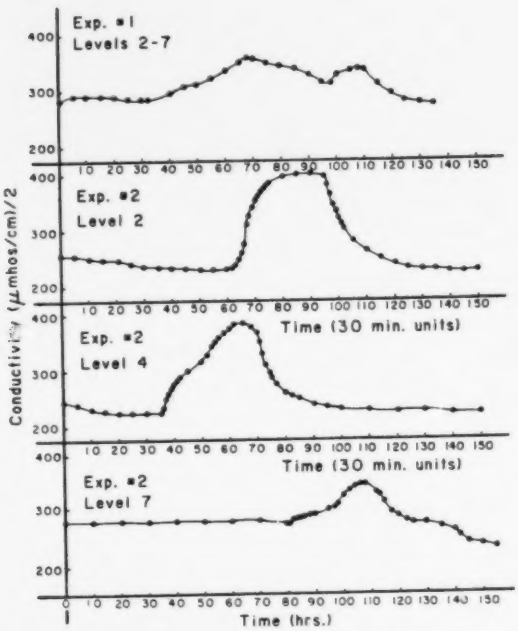

Fig. 6. Conductivity breakthrough curves at various levels of well E3 during experiments 1 and 2.

days in an attempt to be certain that all injected tracer had passed the observation well.

A representative breakthrough curve at E3 for experiment 1 and all curves for experiment 2 are shown in Figure 6 in terms of electrical conductivity readings at the various levels versus time. In experiment 1 there was an apparent breakthrough at each level. However, all curves were very similar in shape (essentially identical to the curve in Figure 6) and most tracer first arrival times were nearly the same (32–33 hours). This is in distinct contrast to experiment 2 where full breakthroughs occurred only at levels 2 and 4 and a partial breakthrough at level 7. (The level numbers are defined in Table 2.) In addition, the first arrival times at levels 2, 4, and 7 were 60, 35, and 80 hours, respectively. Even after 7 days of injection, there was no hint of tracer arrival at any of the other levels. Evidently, the flow pattern that was established bypassed all levels except 2, 4, and 7.

Our major interpretation of the first two preliminary experiments was that nearly complete mixing occurred in the observation well screen during experiment 1. If the apparent breakthrough curves were accepted at face value, one would conclude that the aquifer was nearly homogeneous. The addition of inserts with inflatable packers and silicone rubber plugs (Figures 3 and 5) apparently stopped the mixing rather dramatically. Given the fact that the vertical gradients set up during a fully penetrating test would be expected to be much less than those for a partially penetrating test, it was concluded that our probe isolation system was adequate for the fully penetrating single- and double-well tests that were to follow.

2.3. *Effect of Sample Zone Mixing*

After experiment 2 was completed the packer was removed from 12, and all subsequent tracer injections were fully penetrating. The first experiment in which all systems were fully operational (i.e., inflated packers, sample zone mixing, multi-level sample collection and analysis as well as electrical conductivity readings) was experiment 4. The final experiment that we viewed as preliminary was 3 which was conducted in a manner similar to 4 but without sample zone mixing. In both tests the tracer solution injection rate was approximately 0.915 m^3/min, with injection continuing until apparent breakthroughs occurred at all measurement levels in E3. An average Br injection concentration of 250 mg/L occurred in experiment 3, while a concentration of 242 mg/L applied to 4.

Shown in Figure 7 are the conductivity breakthrough curves at various levels as recorded in experiments 3 and 4. Level 3 is not included and level 6 is not complete because we had some instrumentation or probe problems during the experiments and most of the conductivity readings for those levels were obviously erroneous. Examination of Figure 7 indicates that sampling zone mixing had a definite effect on the breakthrough curves. With the moderate exception of level 2, the first arrival times are essentially identical as one would expect. However, the rate of rise and the peak conductivity value is generally less with mixing than without by more than can be accounted for by the slightly lower injection concentration in experiment 4. An exception to this latter trend was level 4 which experienced a sharper breakthrough curve with mixing than without.

It is evident that sample zone mixing has a significant effect on the midrise arrival time (i.e., that time when the concentration is 50% of its maximum value), which is generally considered to be the best measure of tracer travel time from a point of injection to a sampling point. It appears that there is a substantial contrast in the tracer arrival times at various locations along the 91-cm sampling zones. Thus in the absence of mixing, the details of a breakthrough curve will depend on the location of the probe or sampling point relative to the tracer distribution along the 91-cm length of the zone. For smaller sampling zones the effect of mixing should be less. Further evidence for a substantial shear flow along the zone length may be obtained by calculating the apparent dispersivities at the various levels in the observation well; this was

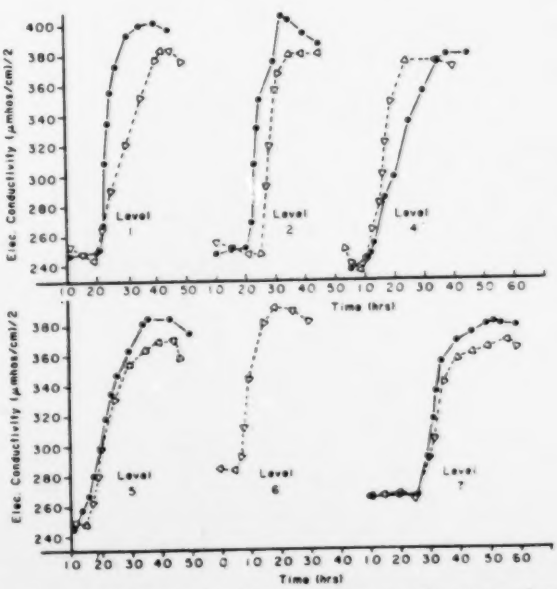

Fig. 7. Conductivity breakthrough curves at various levels of well E3 during experiments 3 (circles) and 4 (triangles). During experiment 3, no mixing was induced.

done for experiment 4 using the actual Br concentration data shown in Figure 10. The apparent longitudinal dispersivities, calculated using an equation given by *Pickens and Grisak* [1981, p. 1195, equation 12], are listed in Table 2. The calculated value at each level depends on how the breakthrough curve at that level is interpreted; an approximate bound for interpretation uncertainty (or error) is listed in the table together with each calculated value. The resulting apparent longitudinal dispersivities vary from 0.04 to 0.50 m, which are much too large to be caused by local hydrodynamic dispersion alone (see, for example, *Pickens and Grisak* [1981], *Molz et al.* [1983*b*], and *Güven et al.* [1984]).

3. Measurement of Relative Hydraulic Conductivity Distribution

As was mentioned previously, experiment 4 was conducted with sample zone mixing as well as regular sample collection and subsequent laboratory analysis. The scheme for mixing and sampling is illustrated in Figure 8. By manipulating the clamps on the exit tubing, water could be routed at will from the peristaltic pump back to the sampling level or to a sampling bottle, without introducing a significant amount of air into the system. In the actual experiment two pump drives with four heads each were used.

During experiment 4 we relied mainly on the actual sample concentration measurements to define the breakthrough curves at the sampling zones, although the consistency of the concentration and conductivity measurements were reasonable; more will be said about this later. Duplicate samples were collected from the sampling zones, as well as the injection-recovery well, and concentrations were determined carefully using a Br specific ion electrode.

Shown in Figure 9 are the bromide concentrations measured in the injection-recovery well, while the concentration breakthrough curves measured in the multilevel observation well are shown in Figure 10. (Water samples were obtained from the injection-recovery well using a faucet in the pipeline.) During the experiment tracer solution at an average concentration of 242 mg/L was injected at the rate of 0.915 m^3/min (241.8 gpm) for the first 32 hours. This injection rate, without tracer added to the water, was maintained for the next 22 hours at which time injection was halted. One hour and 15 min later recovery pumping was initiated at the rate of 1.19 m^3/min (314 gpm) and continued for 2 weeks so that virtually all tracer was removed from the system. Note that Figure 9 contains both injection and recovery data, while Figure 10 contains only injection breakthrough data.

Table 2 contains the time for 50% of breakthrough for each

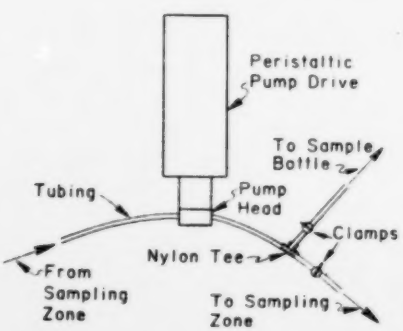

Fig. 8. Diagram illustrating the scheme for causing mixing in the various isolated sampling zones and obtaining samples for laboratory analysis.

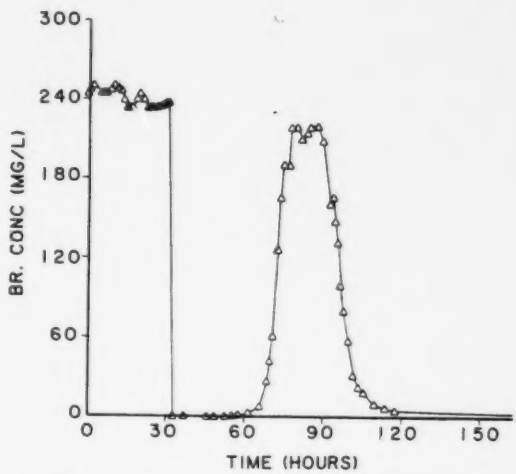

Fig. 9. Br concentration in the injection-recovery well (I2) during experiment 4.

level based on the conductivity measurements for experiment 4 shown in Figure 7 and the concentration data shown in Figure 10. With the probable exception of level 1, the concentration data look quite good. On the average, the arrival times based on conductivity lag those based on concentration by about 2 hours. This is largely due to the fact that the electrical conductivity of the supply water, which is ultimately mixed with tracer, is lower than that of the native groundwater in the vicinity of I2 by about 16%. Thus as the tracer solution approaches a conductivity probe, the reading will decrease initially even though the bromide concentration is increasing. The net effect of this interaction is to cause the electrical conductivity data to overestimate the actual midrise arrival time. Presumably, this could be corrected by adding additional ions, other than bromide, to the supply water. However, we didn't attempt this because the probe recordings were used mainly to orient ourselves qualitatively as to what was happening in the subsurface. Calculations of relative permeability were based on arrival times deduced from the electrical conductivity data as well as the concentration data measured in the laboratory. The results of both are shown in Table 2 mainly for comparison and information purposes. The relative permeabilities were calculated using the formula

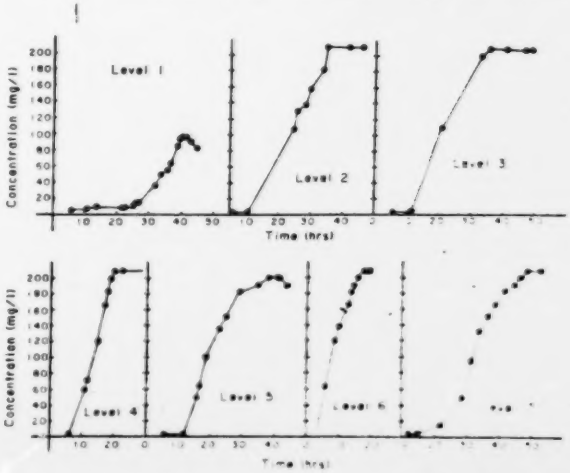

Fig. 10. Br concentration breakthrough curves at the seven levels of well I-3 during experiment 4.

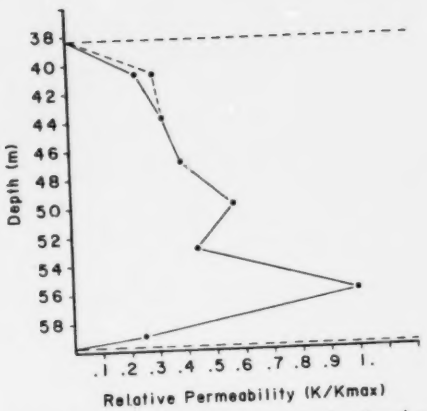

Fig. 11. Inferred relative permeability distribution based on the results of experiment 4.

$K/K_{max} = t_{min}/t_{0.5}$ (see also *Pickens and Grisak* [1981, p. 1201]), where $t_{0.5}$ is the arrival time at a particular level with hydraulic conductivity K, and t_{min} is the smallest arrival time observed during the test at the level with the largest hydraulic conductivity K_{max}.

Figure 11 is a plot of relative permeability (K/K_{max}) as determined from the concentration data of experiment 4. Since the concentration data for level 1 are not consistent with that from the other levels (perhaps a tubing leak?), we used the conductivity data and the 2-hour rule to provide a second estimate of the first level relative permeability. At this level the conductivity data were normal in appearance and resulted in the dashed portion of the curve shown in Figure 11.

4. Discussion and Conclusions

The results displayed in Figure 11 indicate the presence of a high permeability zone in the bottom third of the aquifer, along the line connecting E3 and I2. However, a two-well test, to be reported separately, which involved injection through E1 and recovery through I2 resulted in a relative permeability distribution very similar to that of Figure 11. Thus the permeability trend which has been identified appears to persist at least in the direction of and over the distance between E1 and I2. This result is consistent with findings from previous thermal energy storage experiments at the Mobile site which indicated the presence of a high permeability zone, although at a slightly higher elevation in the aquifer [*Molz et al.*, 1983*a*; *Buscheck et al.*, 1983].

In displaying the data of Figure 11 it was decided to simply draw straight lines between the points where hydraulic conductivity was known or measured. In doing this, use was made of nine points: the top and bottom of the aquifer, where the clay confining layers force the permeability to essentially zero, and the seven sampling points where tracer travel times were recorded. Because of the spacing of the data points, a significant amount of information could have been missed. Recently, an insert design was developed which will allow us to double the number of sampling zones in future experiments. We also hope to gain a better understanding of present data limitations by performing computer simulations of several of our experiments, particularly a two-well test that was performed recently; such simulations are now underway.

In our experiments we found that sample zone mixing affected the results, so mixing was employed throughout the main experiments. Presumably, such mixing would become progressively less important as the sample zone volume decreased and as travel distance increased for a given sample zone size. In our two-well tests, which involved a tracer travel distance of about 33 m, the total breakthrough time was so short compared to the total travel time that it did not matter what part of the breakthrough curve was used to calculate relative permeability. In such a situation sample zone mixing may not be important.

As a final note, it is worth mentioning that a single-well test was performed using E1 as an injection-recovery well and E5 as a multilevel observation well. During Br concentration measurements it was noticed that a cloudy material was present in the samples obtained from E5, and the data made no sense. Further analysis indicated the presence of clay in the samples and also in the bottom of the well. Evidently, the well was not developed sufficiently to remove all the drilling mud from the formation; because of this the experiment data had to be abandoned. It is not desirable to overdevelop the formation around a tracer observation well. However, it must be developed sufficiently to remove all drilling mud.

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R. D. Crocker, O. Güven, K. T. Matteson, J. G. Melville, and F. J. Molz, Department of Civil Engineering, Auburn University, Auburn, AL 36849.

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